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Actual Effectiveness of Hearing Protection in High Level Impulse Noise

(Reprint)

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Current exposure limits for high intensity impulse noise contain factors for hearing protection which are based on very limited data. Recent studies in the U.S. and in France have provided new insights into the protection afforded by hearing protective devices. For impulses with an A-duration of approximately 3.0 ms, protection was found to be adequate for peak pressures up to 190 dB SPL for 6 impulses and 187 dB for 100 impulses. Protection was found to be adequate for 6 impulses with an A-duration of approximately 0.8 ms up to 196 dB SPL. For this A-duration, protection was adequate for 12 impulses up to 190 dB SPL and for 50 and 100 impulses at 187 dB SPL. The hearing protectors used in these studies were earmuffs with perforations in the cushions which provided essentially no attenuation below 500 Hz. In a series of French studies, hearing protection was found to be adequate for impulses produced by a variety of weapons with peak pressures ranging from 165 dB SPL to 180 dB SPL. These included small arms with A-durations less than 1.0 ms, artillery with A-durations of approximately 3.0 ms and other weapons with durations between these extremes. A variety of insert hearing protectors (earplugs) was used in
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these studies. All had perforations which resulted in poor low frequency attenuation. In both sets of studies, conventional attenuation rating schemes greatly underestimated the actual protection afforded by the hearing protective devices. Direct measurements of the pressures under the earmuff showed these peak levels can be as high as 182 dB SPL without significant effects on hearing.

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ABSTRACT

Current exposure limits for high intensity impulse noise contain factors for hearing protection which are based on very limited data. Recent studies in the U.S. and in France have provided new insights into the protection afforded by hearing protective devices. For impulses with an A-duration of approximately 3.0 ms, protection was found to be adequate for peak pressures up to 190 dB SPL for 6 impulses and 187 dB for 100 impulses. Protection was found to be adequate for 6 impulses with an A-duration of approximately 0.8 ms up to 196 dB SPL. For this A-duration, protection was adequate for 12 impulses up to 190 dB SPL and for 50 and 100 impulses at 187 dB SPL. The hearing protectors used in these studies were earmuffs with perforations in the cushions which provided essentially no attenuation below 500 Hz. In a series of French studies, hearing protection was found to be adequate for impulses produced by a variety of weapons with peak pressures ranging from 165 dB SPL to 180 dB SPL. These included small arms with A-durations less than 1.0 ms, artillery with A-durations of approximately 3.0 ms, and other weapons with durations between these extremes. A variety of insert hearing protectors (earplugs) was used in these studies. All had perforations which resulted in poor low frequency attenuation. In both sets of studies, conventional attenuation rating schemes greatly underestimated the actual protection afforded by the hearing protective devices. Direct measurements of the pressures under the earmuff showed these peak levels can be as high as 182 dB SPL without significant effects on hearing.

Efficacoté Réelle des Protecteurs Auditifs Pour des Expositions à des Bruits Impulsionnels de Niveau de Crête élevé

RÉSUME

Les critères d'exposition usuels aux bruits impulsionnels de fort niveau permettent de tenir compte de la protection auditive utilisée mais seulement à partir de résultats très limités. Des

études récentes réalisées aux Etats-Unis et en France ont apporté de nouvelles indications quant à la protection effective fournie par les protecteurs auditifs. Pour des impulsions d'une durée de première phase positive (durée A) d'environ 3 ms, la protection employée était adéquate pour des niveaux de surpression de crête allant jusqu'à 190 dB SPL pour 6 coups et jusqu'à 187 dB SPL pour 100 coups. La protection était également adéquate pour 6 coups d'ume durée A d'environ 0,8 ms et de 196 SPL de surpression de crête. Pour la même durée, la protection était adéquate pour 12 coups jusqu'à 190 dB SPL et pour 50 et 100 coups jusqu'à 187 dB SPL. Les protecteurs auditifs utilisés dans ces études étaient des serre-tête dont les coussinets avaient été perforés et qui, de ce fait, n'apportaient pas d'atténuation pour les fréquences inférieures à 500 Hz. Dans une série d'études réalisées en France, la protection auditive était adéquate pour des expositions à des bruits impulsionnels produits par des armes et dont les surpressions de crête allaient de 165 à 180 dB SPL. Ces bruits correspondaient soit à ceux produits par des armes légères (durée A inférieure à 0,1 ms), soit à ceux produits par des pièces d'artillerie (durée A d'environ 3 ms), ainsi qu'à ceux d'autres armes de durées A intermédiaires. Dans ces études, les protecteurs auditifs utilisés étaient des bouchons d'oreilles de différents types qui comportaient tous des perforations induisant une faible atténuation aux basses fréquences. Dans ces deux types d'études, l'atténuation des protecteurs auditifs mesurée de facon conventionnelle sous-estimait la protection effective apportée par les protecteurs. Des mesures directes de pression réalisees sous la coquille des serre-tête ont montré que les niveaux de crête pouvaient atteindre 182 dB SPL sans que l'on observe d'effet significatif sur l'audition des sujets.

Introduction: In 1968, CHABA published a "Proposed damage risk criterion for impulse noise (gunfire)" derived from Coles et al. (1968). This criterion was based on data from exposure of unprotected humans and made no provision for extending the limit when hearing protection is used. Three basic approaches have been used to resolve this shortcoming. The first was to estimate the protection and simply raise the unprotected exposure limit by the amount of the protection. The second approach was to expose people with protection to an impulse noise and look for effects on their hearing. Finally, the impulse noise penetrating the protector can be measured and the unprotected limits applied to this measured pressure-time signature.

Fixed protective values: The development of the military standard, which establishes the exposure limits for military equipment in the United States, is an example of the first approach. Based on the results of a study of exposure to shoulder-fired antiarmor weapon noise with earplugs, Garinther and Hodge (1971) concluded that hearing protectors provided 29 dB of protection. This amount of protection was incorporated into MIL-STD-1474 to establish our current exposure limits by raising the CHABA (1968) criterion by this amount (Garinther and Hodge, 1981). Thus, twenty-nine dB of protection is accorded to any protector regardless of its attenuation characteristic. In Germany, Pfander (1975) developed an impulse noise exposure limit using 25 dB as the amount of protection. The protected limit is simply the unprotected limit raised by 25 dB.

Direct determination studies: In the 1970s, the impulse noise produced by new heavy weapons became a matter of concern to the U.S. Army because it exceeded the protected exposure limits. This led to studies designed to determine whether then current hearing

protection was adequate for these weapons. Patterson et al., (1985) showed that foam earplugs provided adequate protection for artillery noise which exceeded the limit. Patterson and Mozo (1987) showed that the same protection was adequate for the noise of a shoulder-fired antiarmor weapon which also exceeded the protected limit. These results are clearly contradictory to our current exposure limits. One possible explanation is that the 29 dB protection factor is not correct for all hearing protectors. It is known that the foam earplugs provide large amounts of attenuation when they are properly used as they were in these studies. Unfortunately, direct estimates of the amount of protection cannot be derived from these results. While these studies showed that the earplugs used provided adequate protection, they did not establish an upper bound on the noise levels for which they are adequate.

In order to establish upper bounds for exposure to the high intensity impulse noise typical of most heavy weapons, a series of studies was undertaken in the United States. These studies used a common approach with only the exposure impulse changing between studies. Both the level and the number of impulses were varied. Volunteers were given a series of exposures starting with six impulses at a level below current exposure limits. On successive exposure days, the level was raised while the number of impulses remained fixed at six. This process was repeated until a significant threshold shift (over 25 dB at any frequency) was observed or until the threshold of nonauditory injury (Dodd et al., 1990) was reached. Then the number of impulses was increased and exposures continued at a reduced level. The numbers of impulses used were 6, 12, 25, 50, and 100. The goal was to find the lowest level for each number of impulses which resulted in a significant threshold shift (TS). Approximately 60 volunteers, military personnel with less than 5 years of service, participated in each study.

Table 1. Average peak pressures and durations for the impulses at 5 meters from the source.

Intensity code	Peak (kPa)	Peak (dB)	A-duration (ms)	B-duration (ms)	C-duration (ms)	D-duration (ms)
1	10	174	2.3	15.6	1.7	6.0
2	14	177	2.5	17.4	2.0	7.8
3	19	180	2.6	17.2	2.1	7.8
4	26	182	2.9	18.0	2.3	7.6
5	36	185	2.8	18.9	2.6	8.2
6	49	188	2.9	20.0	2.8	9.9
7	69	191	3.0	21.2	2.8	8.3

The first of these (Patterson and Johnson, 1990) used impulses typical of artillery weapons. These impulses were produced by detonation of explosive material 5 meters from the location of the volunteers and approximately 3 meters above the ground. Figure 1a shows a typical pressure-time signature for this impulse. Table 1 shows the average levels and durations for the series of intensities.

The study design initially included three levels of hearing protection. The plan was to find the limit of the poorest protector first; then to find the limit for improved protection; and finally, to find the limit for the maximum protection. The first hearing protector used was an earmuff compatible with the U.S. Army infantry helmet. The second and third levels were the foam earplugs and the foam earplugs combined with the earmuff; however, these were never used for reasons which will become obvious. Figure 2 shows the attenuation of the earmuff.

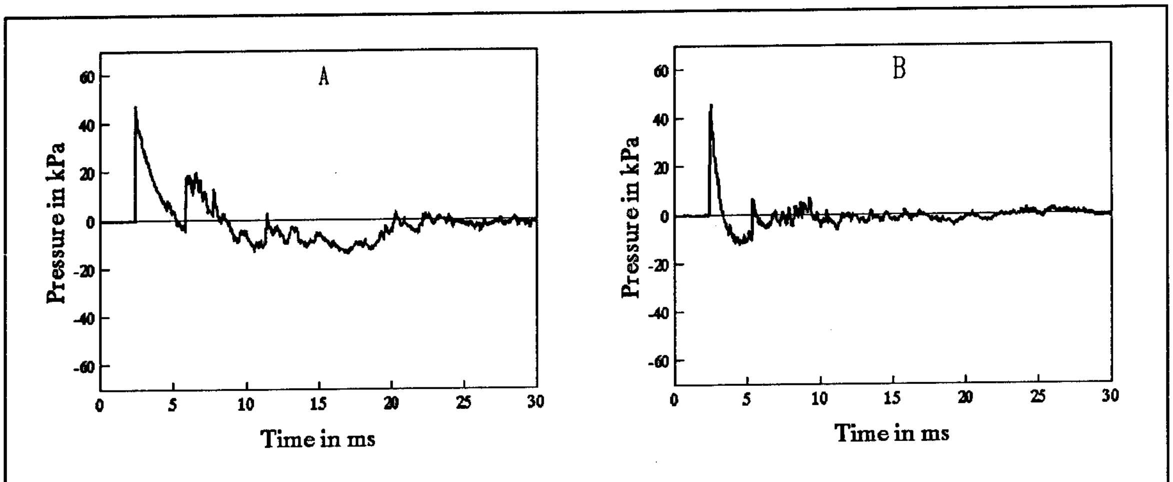

Figure 1. Pressure–time signatures: 5 meters (panel A) and 1 meter (panel B) from source

The first group of volunteers started the study using the earmuff. Forty-nine of these were exposed to 6 impulses at 190 dB SPL and 39 also were exposed up to the 100 impulses at 187 dB SPL. None showed any significant TS. This led to a change in the study design. The hearing protection became the same earmuff modified by introducing intentional leaks in the ear seals. The attenuation at octave frequencies for the modified earmuff also is shown in Figure 2. Notice the low frequency attenuation has been eliminated and the high frequency attenuation reduced. This attenuation is typical of what might be found with a poor fit of the standard earmuff in which the seal is compromised. Another group of 60 volunteers was exposed wearing the modified earmuff. This time 56 volunteers progressed to the exposure to 6 impulses at 190 dB SPL with only one showing a significant TS; 58 were exposed up to 100 impulses at 187 dB SPL with only 2 showing a significant TS. These results were interpreted to indicate that the modified earmuffs provide adequate protection for all exposure conditions used in this study.

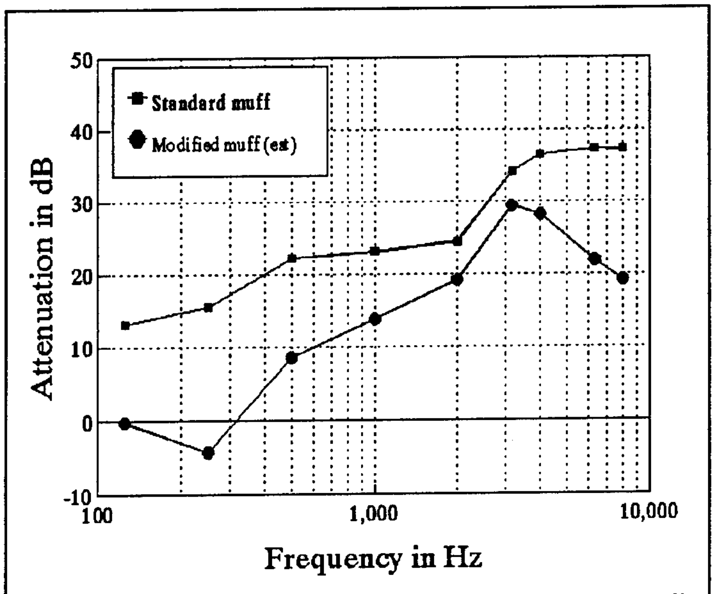

Figure 2. Average attenuation for standard and modified earmuffs

For the next study (Patterson and Johnson, 1993), the exposure stimuli were produced by detonating explosive material inside a 60 cm diameter steel tube. The volunteers were located so their heads were approximately 1 meter from the open end of the tube. The pressure-time signature for this impulse is shown in Figure 1b. Table 2 contains the levels and durations for the intensity levels used in this study. The first level hearing protection was the modified earmuffs described earlier. All other procedures remained the same.

Table 2. Average peak pressures and durations for the impulses at 1 meter from the source.

Intensity code	Peak (kPa)	Peak (dB)	A-duration (ms)	B-duration (ms)	C-duration (ms)	D-duration (ms)
1	16	178	1.1	10.8	1.2	2.5
2	23	181	1.0	12.1	1.0	2.2
3	34	185	0.9	9.5	0.7	1.9
4	48	188	0.9	10.8	0.6	1.3
5	66	190	0.8	15.4	0.6	0.8
6	94	193	0.8	53.8	0.5	0.7
7	130	196	0.8	65.0	1.0	1.2

Sixty-five volunteers started the study and 59 progressed to the exposure to 6 impulses at 196 dB SPL. Of these, four showed significant TS at the highest level. Statistically the hypothesis that 95 percent of the exposed population is protected adequately can be rejected when 6 or more volunteers show a significant TS. Therefore, the modified earmuffs provide adequate protection for 6 impulses at 196 dB. For exposure to 12 impulses at 193 db SPL, 6 of the 61 volunteers showed a significant TS. The protection is considered inadequate for this condition as well as the 193 dB level for more than 12 impulses. At 190 dB SPL, only 4 of 59 volunteers showed a significant TS after exposure to 25 impulses; while at 50 impulses resulted in 7 out of 55 volunteers with a significant TS. At this level, the protection becomes inadequate between 25 and 50 impulses. At 188 dB SPL, the modified earmuff provided adequate protection for all numbers of impulses; 50 impulses produced significant TS in only 3 of 51 volunteers and 100 impulses at this level resulted in significant TS in only 3 of 44 volunteers. These results are summarized in Table 3. The protection provided by the unmodified earmuff was considered adequate for all exposure conditions included in this study.

Table 3. Summary of conditions for which the modified earmuffs provide adequate protection for combinations of level and number of impulses.

	Number of impulses				
Level	6	12	25	50	100
196	A	NA	NA	NA	NA
193	A	U	U	U	U
190	A	A	A	U	U
188	A	A	A	A	A

A=adequate, U=inadequate, NA=exceeds nonauditory limit

While these studies were being conducted in the U.S., French researchers were conducting a complementary set of studies (Dancer et al., 1992). The U.S. studies focused on large numbers of volunteers exposed under the same conditions for statistical reliability and included only two hearing protector conditions, both earmuffs. In contrast, the French studies used more different hearing protectors, all earplugs, with a smaller number of volunteers for each exposure condition. They also focused on protectors with little or no low frequency attenuation in an effort to maintain face-to-face voice communication. The U.S. studies used explosives to achieve exposure levels exceeding those produced by existing weapons; the French studies used a variety of weapons.

Figure 3 shows the attenuation of the hearing protectors used in the first French experiment. Note that the foam plug is the same as that used by Patterson et al. (1985) and Patterson and Mozo (1987). The other protectors are designed to have low attenuation compared to the foam plug. In this experiment, between 6 and 20 volunteers were exposed to the firing of the howitzer for 10 to 20 rounds. The peak levels were between 175 and 176 dB SPL. No TS exceeding 15 dB was observed after these exposures. These results for the foam earplug are not surprising in view of the findings of Patterson et al. (1985); however, the results for the Gunfender are surprising since it has no attenuation up to 1.0 kHz. This may be a result of its reported growth of attenuation with level (Forrest and Coles, 1969).

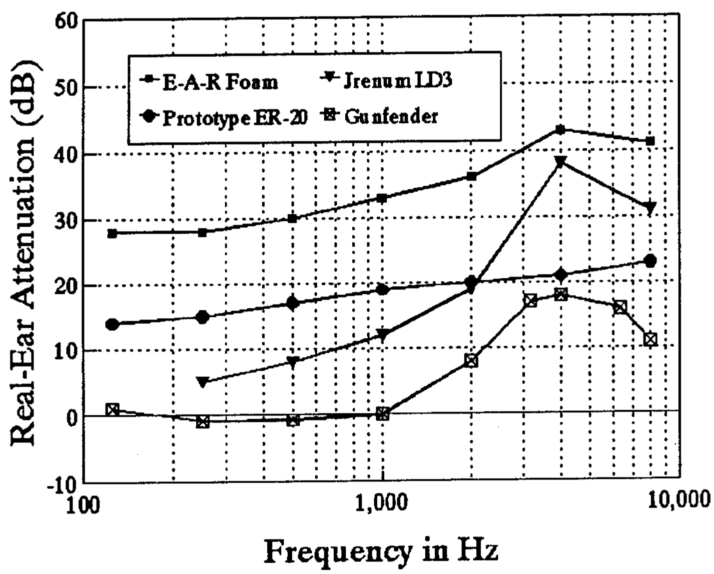

Figure 3. Attenuation of the protectors in the first experiment

In the second experiment, Dancer et al. (1992) used five different hearing protectors. Figure 4 shows the attenuation of these protectors. Three to 5 volunteers were exposed to the rifle fired in a reverberant space (peak levels of 150 to 161 dB SPL), an antitank weapon (peak levels of 182 to 183 dB SPL at the right ear and 178 to 181 dB SPL at the left ear), and to the howitzer (peak levels of 175 to 176 dB SPL). None of the volunteers showed a TS which exceeded the 25 dB criterion used in the U.S. studies to define unacceptable TS. There is no evidence that any of the protectors used in these experiments fail to provide adequate protection. These studies indicate that a variety of protectors with little attenuation at the low frequencies can provide adequate protection for high intensity weapons noise.

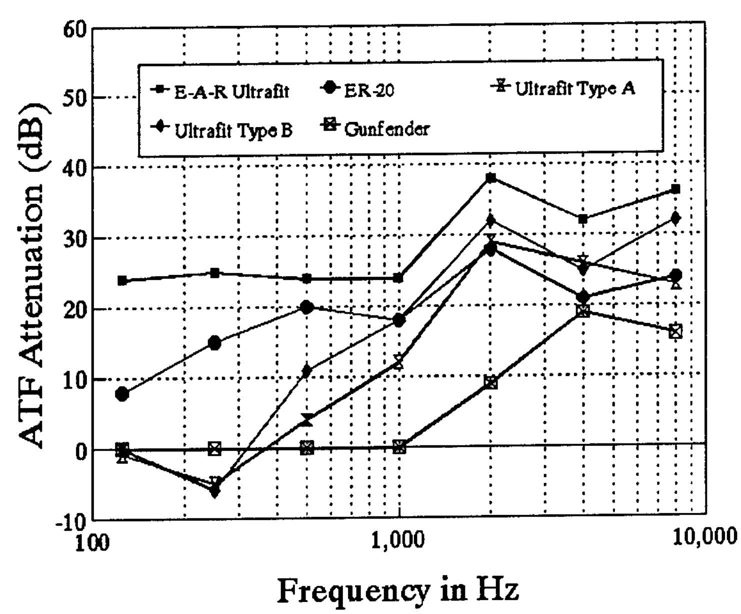

Figure 4. Attenuation of the protectors in the second experiment

Levels under hearing protection: The third approach to estimating the effectiveness of hearing protectors for high intensity impulse noise is to measure the pressure-time signature under the protector and compare the measured parameters to the unprotected exposure limit. This approach differs from the approach of raising the unprotected limit by a protection value in that it is based on the specific protector and the specific impulse. Recently, Pekkarinian et al. (1992) applied this method to heavy weapons noise and concluded that the levels under the earmuffs exceeded the unprotected limits from both CHABA and Pfander. Johnson and Patterson (1992) also have reported that the levels under the earmuffs of the volunteers participating in the studies described above greatly exceed the unprotected limits. However, in this case the lack of any effect on hearing was documented. This indicates that levels measured under hearing protectors should not be compared to unprotected limits to estimate the effectiveness of the hearing protection.

Summary: There is no generally accepted method for calculating the protection against high intensity impulse noise afforded by hearing protectors. Of the three possible approaches, the use of fixed protection values independent of the hearing protector, have been shown to underestimate the actual effectiveness of hearing protectors. Studies designed to determine the actual effectiveness of hearing protectors are the best, but most costly approach. These studies have shown that protection is adequate for levels which exceed our current exposure limits. Further, these studies clearly demonstrate that the hazard of impulse noise cannot be evaluated by measuring under the hearing protector and using unprotected exposure criteria. This approach generally will lead to a gross underestimate of the actual effectiveness of the hearing protector.

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